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Van Brocklin et al.

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(54) **FLUID LEVEL SENSOR AND RELATED METHODS**

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B41J 2/175	(2006.01)

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(58) **Field of Classification Search**
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USPC 347/7, 19, 85, 86
See application file for complete search history.

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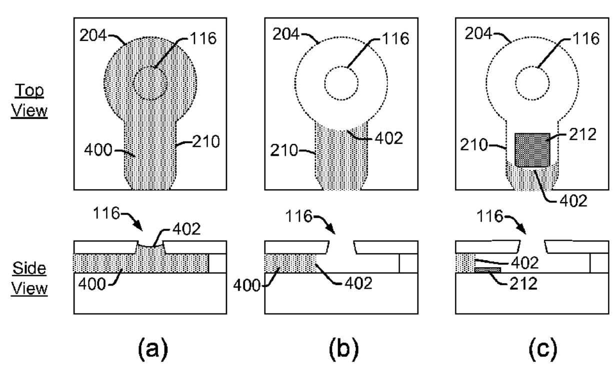
(57) **ABSTRACT**

In an embodiment, a fluid level sensor includes a sensor plate and a current source. The fluid level sensor also includes an algorithm to bias the current source such that current applied to the sensor plate induces a maximum difference in response voltage between a dry sensor plate condition and a wet sensor plate condition.

18 Claims, 13 Drawing Sheets



(51) **Int. Cl.**
B41J 2/045 (2006.01)
B41J 2/14 (2006.01)

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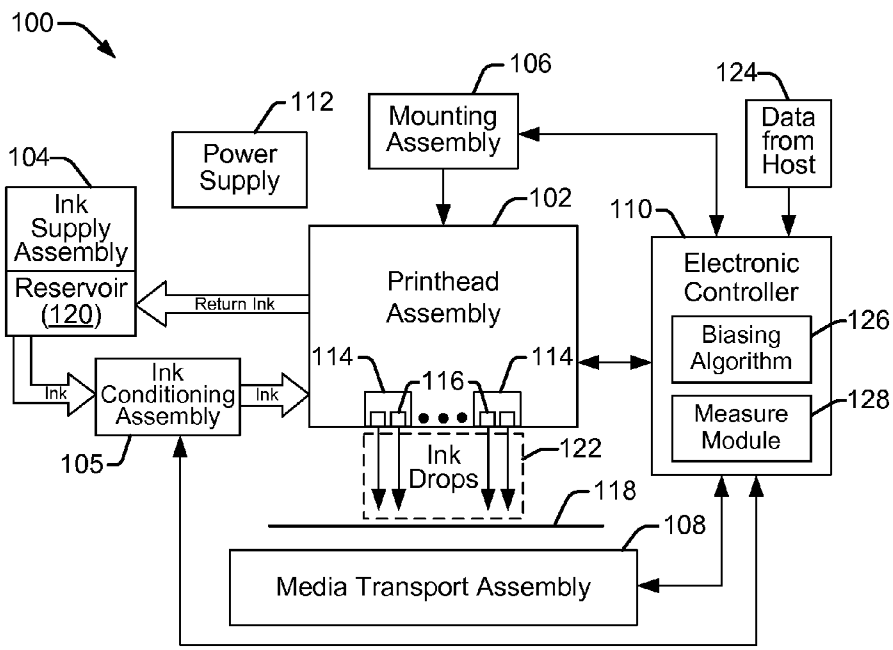

100
112
Power Supply
106
Mounting Assembly
124
Data from Host
104
Ink Supply Assembly
Reservoir (120)
Return Ink
102
Printhead Assembly
110
Electronic Controller
Biasing Algorithm
126
Measure Module
128
114
116
114
Ink
Ink Conditioning Assembly
Ink
105
Ink Drops
122
118
108
Media Transport Assembly

FIG. 1

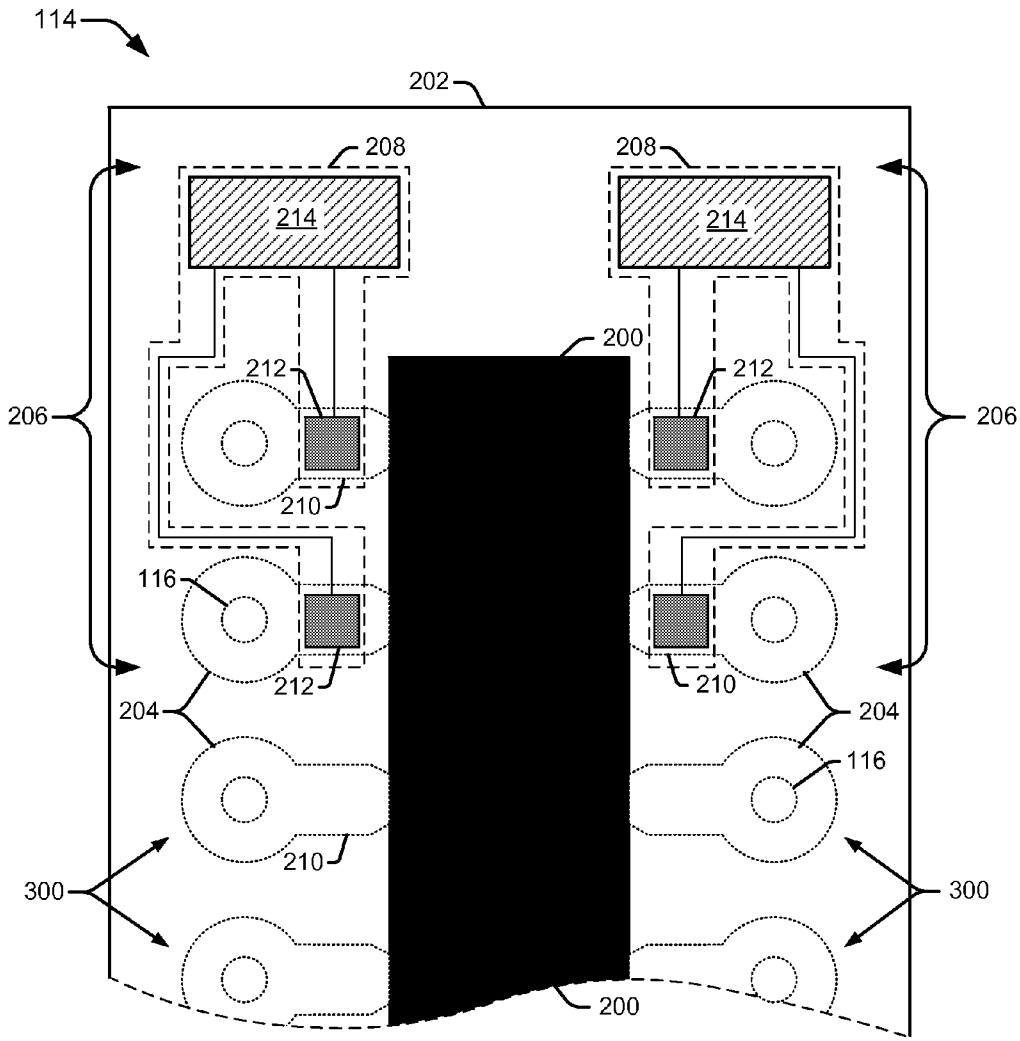

114
202
208
214
208
214
200
212
212
206
206
210
116
210
212
204
204
116
210
300
300
200

FIG. 2

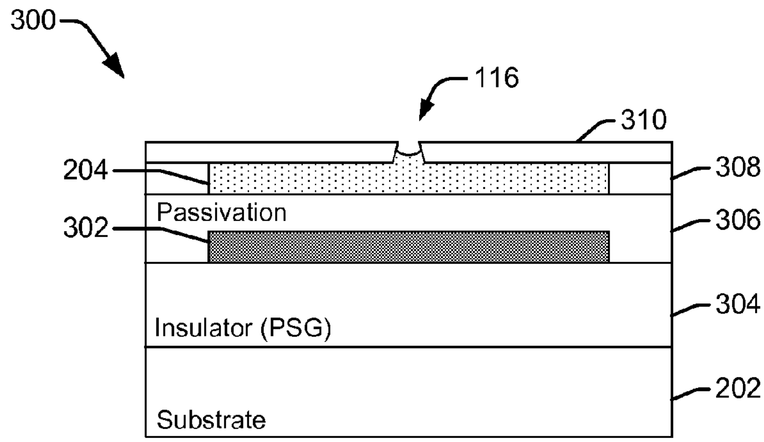

300
116
310
204
308
Passivation
302
306
304
Insulator (PSG)
202
Substrate

FIG. 3

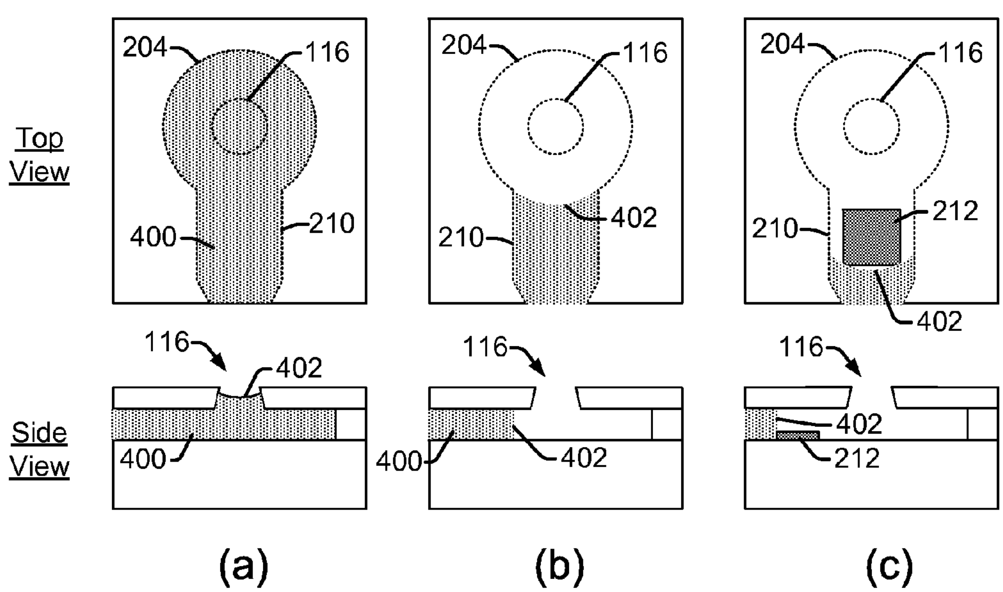
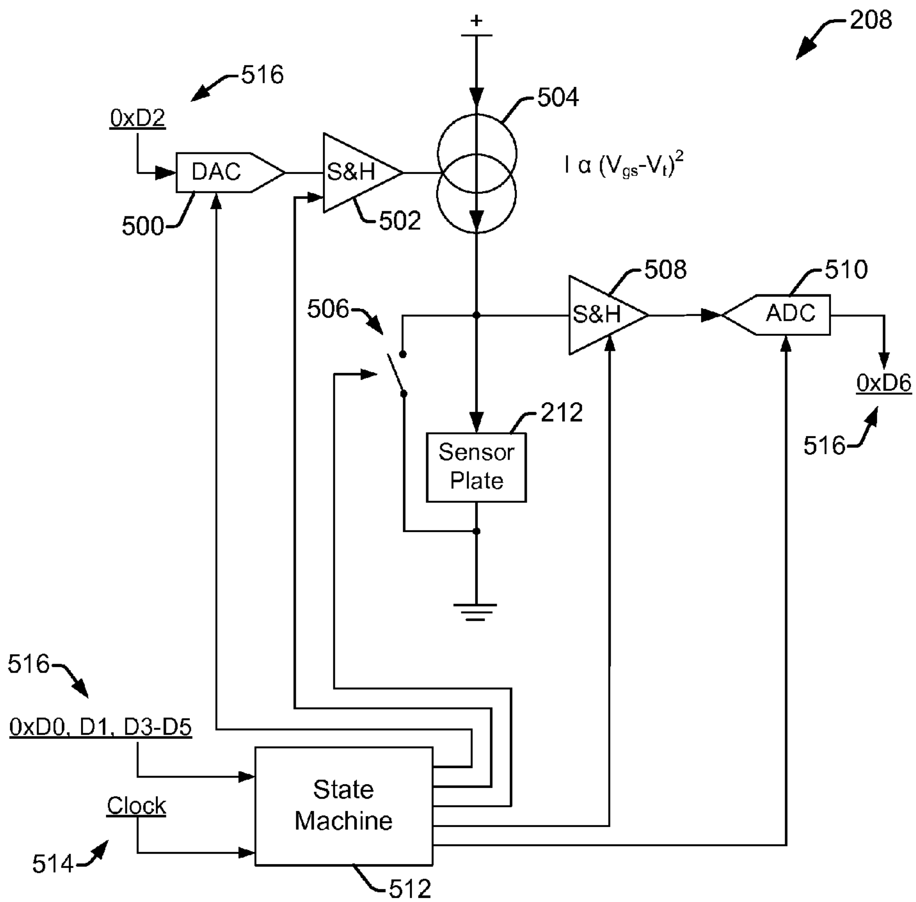

Top View
204
116
400
210
204
116
210
402
204
116
210
212
402
Side View
116
402
400
116
400
402
116
402
212
(a)
(b)
(c)

FIG. 4



208
516
0xD2
DAC
500
S&H
502
504
+
I α (Vgs-Vt)2
506
508
S&H
510
ADC
0xD6
516
212
Sensor Plate
516
0xD0, D1, D3-D5
Clock
514
State Machine
512

FIG. 5

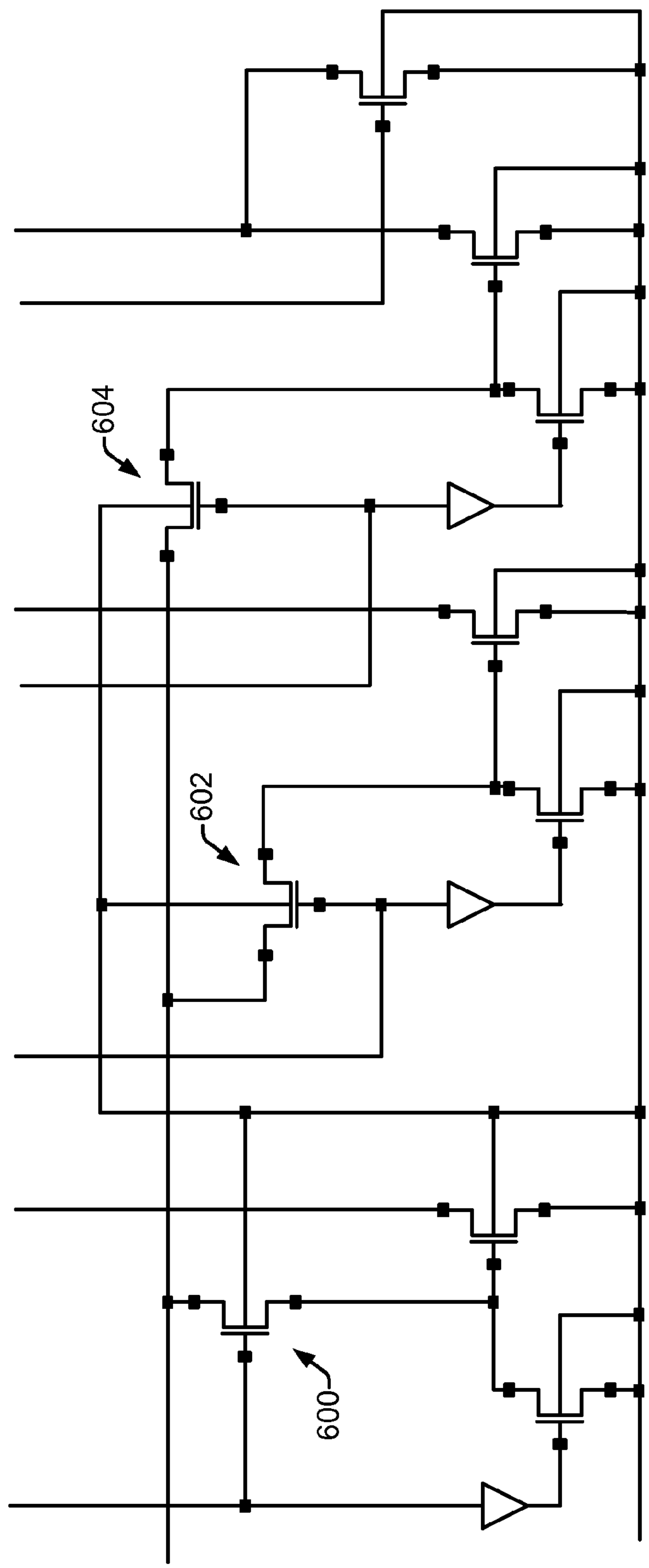


FIG. 6

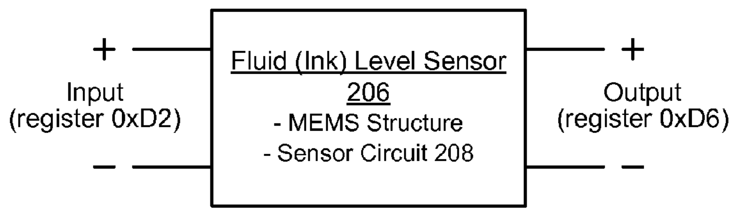

+
Input
(register 0xD2)
−
Fluid (Ink) Level Sensor
206
- MEMS Structure
- Sensor Circuit 208
+
Output
(register 0xD6)
−

FIG. 7

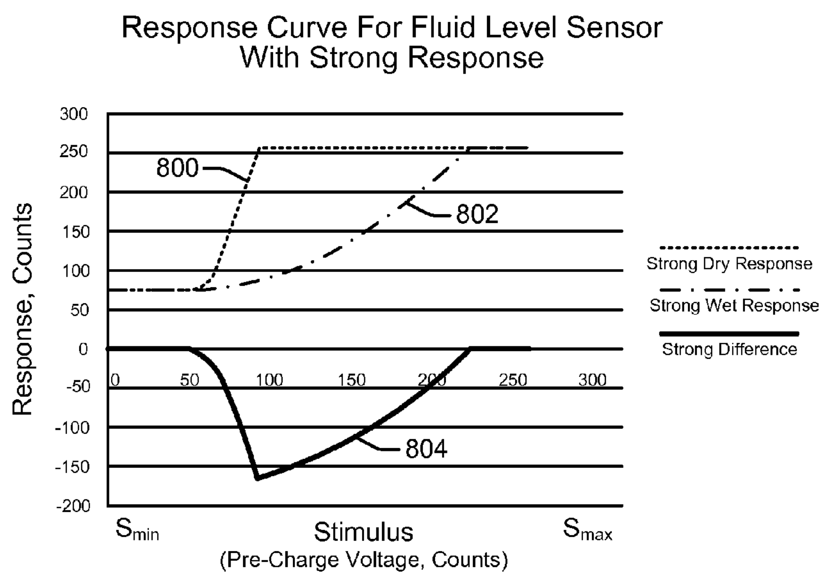

Response Curve For Fluid Level Sensor
With Strong Response
300
250
200
150
100
50
0
-50
-100
-150
-200
Response, Counts
800
802
804
0
50
100
150
200
250
300
Strong Dry Response
Strong Wet Response
Strong Difference
Smin
Stimulus
(Pre-Charge Voltage, Counts)
Smax

FIG. 8

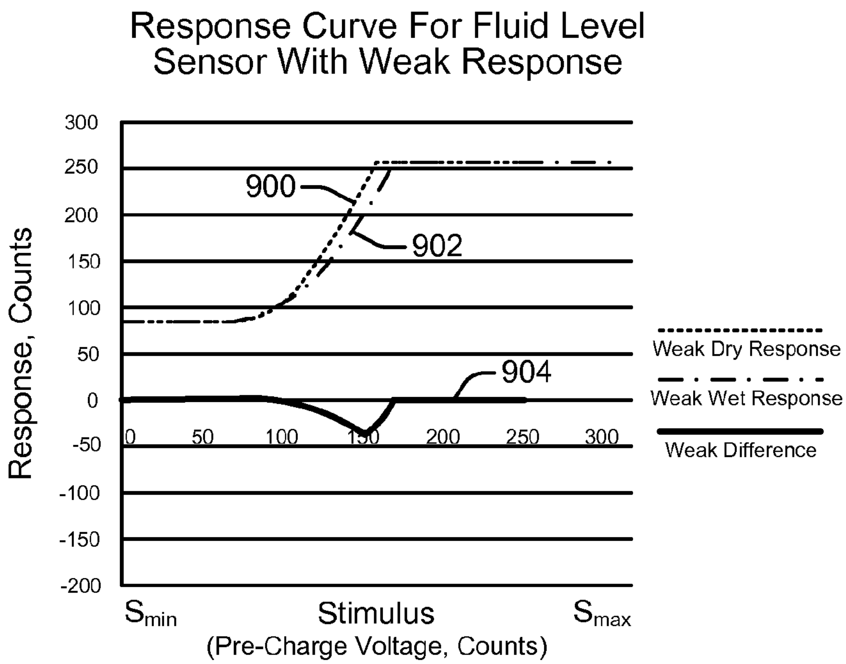

Response Curve For Fluid Level
Sensor With Weak Response
300
250
200
150
100
50
0
-50
-100
-150
-200
Response, Counts
900
902
904
0
50
100
150
200
250
300
Weak Dry Response
Weak Wet Response
Weak Difference
S_{min}
Stimulus
(Pre-Charge Voltage, Counts)
S_{max}

FIG. 9

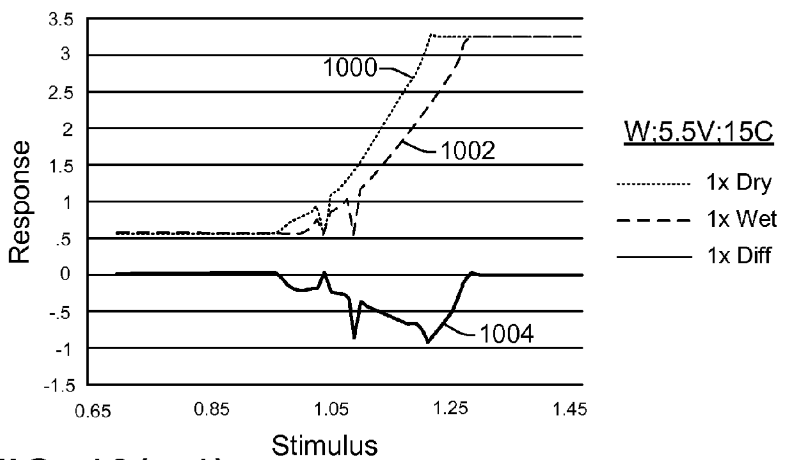


FIG. 10(a.1)

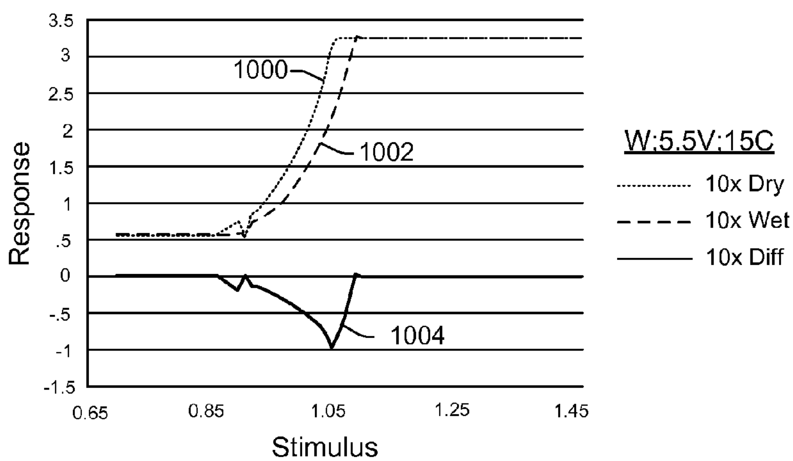


FIG. 10(a.2)

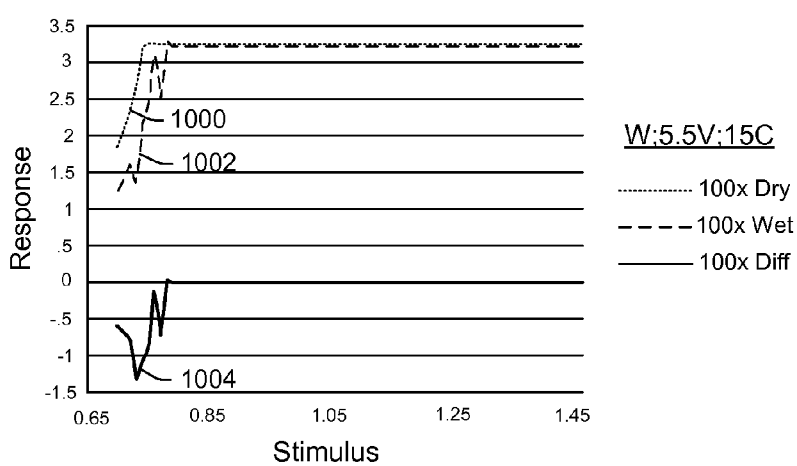


FIG. 10(a.3)

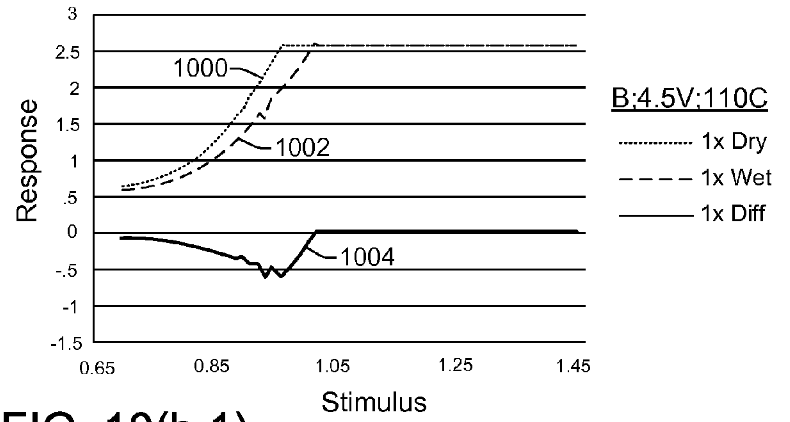


FIG. 10(b.1)

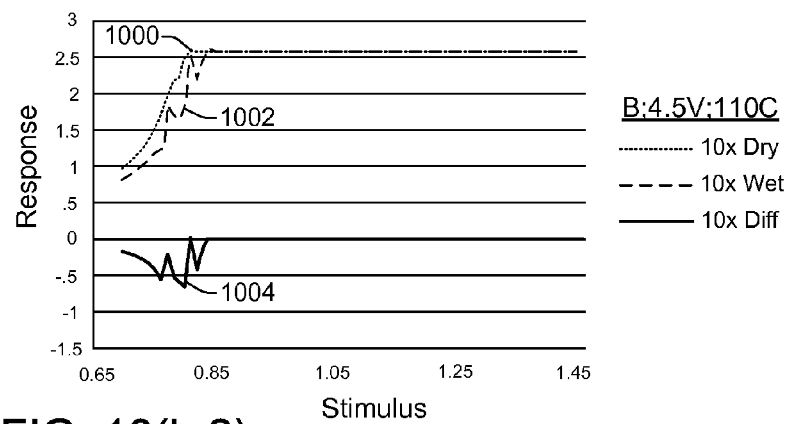


FIG. 10(b.2)

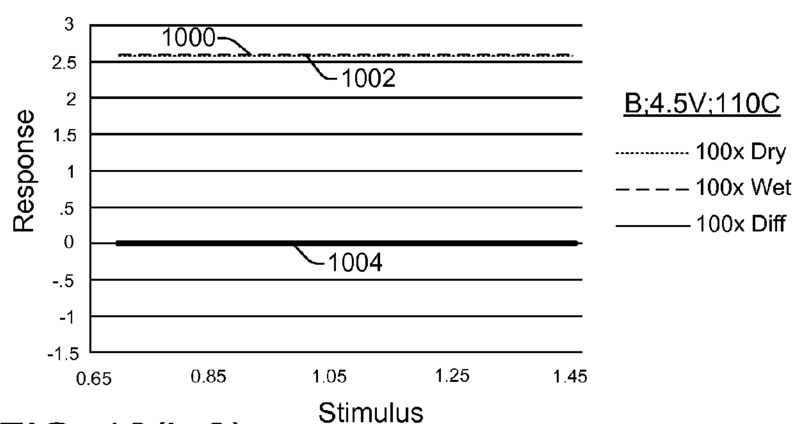


FIG. 10(b.3)

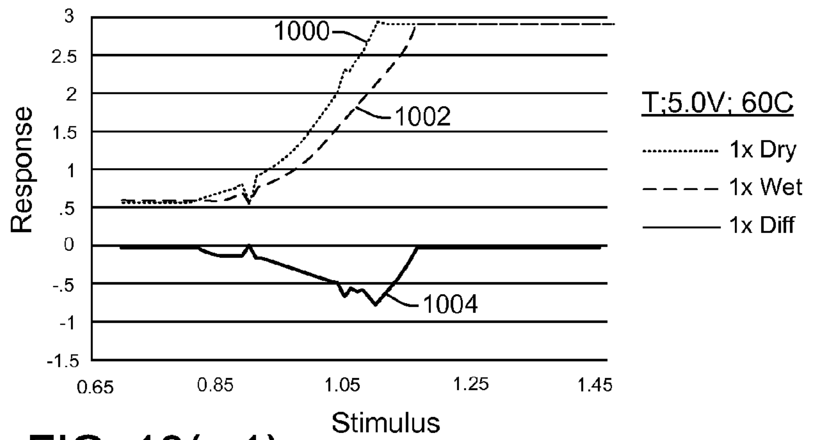


FIG. 10(c.1)

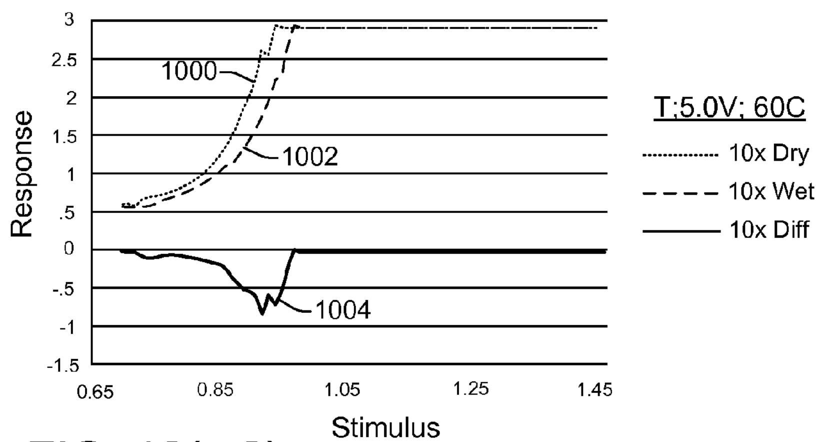


FIG. 10(c.2)

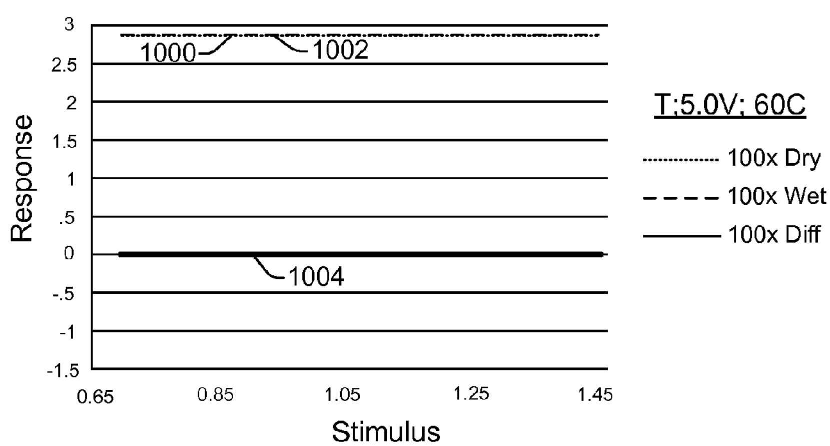


FIG. 10(c.3)

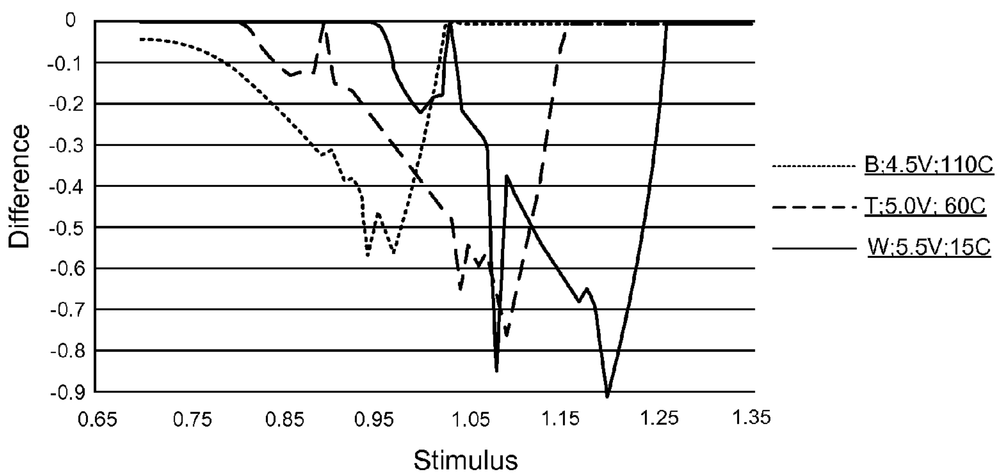

0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
Difference
0.65
0.75
0.85
0.95
1.05
1.15
1.25
1.35
Stimulus
B;4.5V;110C
T;5.0V; 60C
W;5.5V;15C

FIG. 11

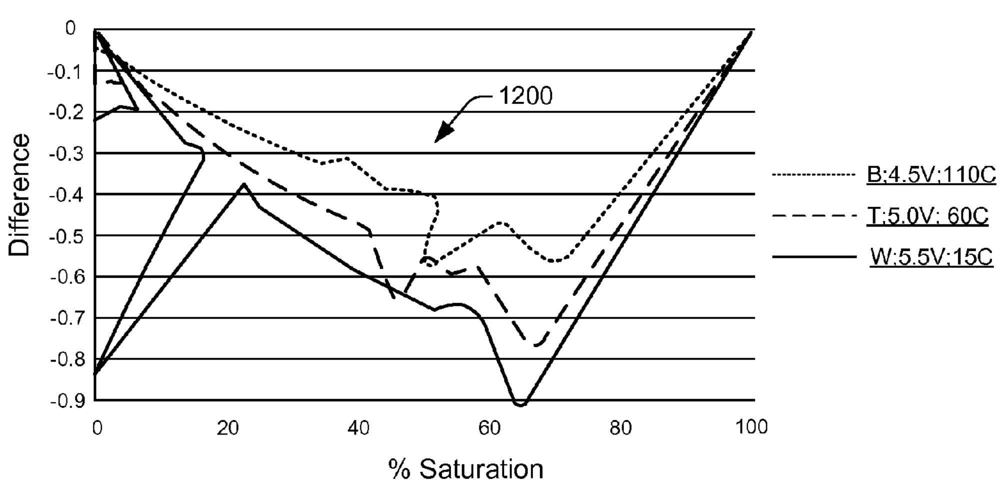

0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
Difference
1200
0
20
40
60
80
100
% Saturation
B;4.5V;110C
T;5.0V; 60C
W;5.5V;15C

FIG. 12

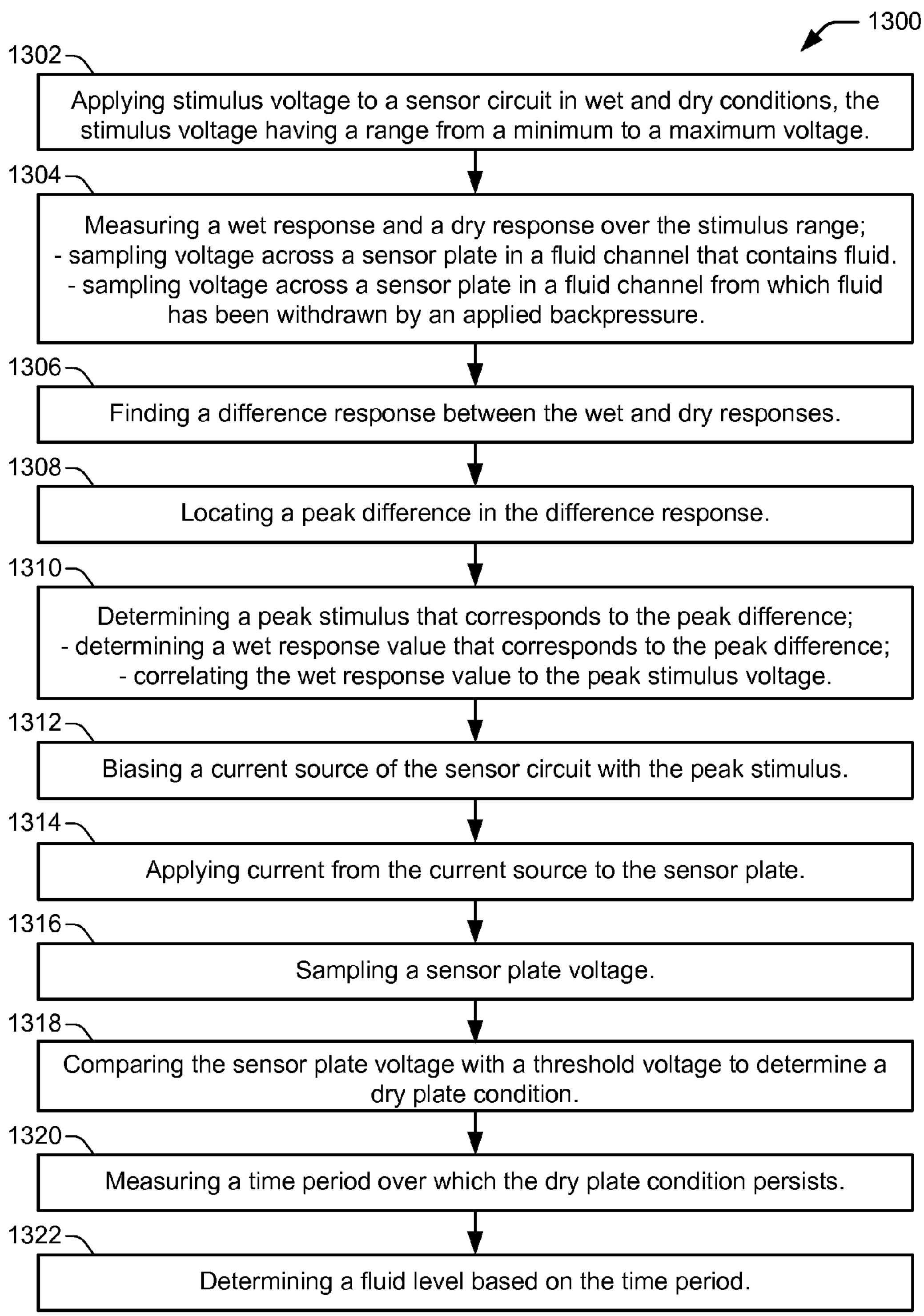

1300
1302
Applying stimulus voltage to a sensor circuit in wet and dry conditions, the stimulus voltage having a range from a minimum to a maximum voltage.
1304
Measuring a wet response and a dry response over the stimulus range;
- sampling voltage across a sensor plate in a fluid channel that contains fluid.
- sampling voltage across a sensor plate in a fluid channel from which fluid has been withdrawn by an applied backpressure.
1306
Finding a difference response between the wet and dry responses.
1308
Locating a peak difference in the difference response.
1310
Determining a peak stimulus that corresponds to the peak difference;
- determining a wet response value that corresponds to the peak difference;
- correlating the wet response value to the peak stimulus voltage.
1312
Biasing a current source of the sensor circuit with the peak stimulus.
1314
Applying current from the current source to the sensor plate.
1316
Sampling a sensor plate voltage.
1318
Comparing the sensor plate voltage with a threshold voltage to determine a dry plate condition.
1320
Measuring a time period over which the dry plate condition persists.
1322
Determining a fluid level based on the time period.

FIG. 13

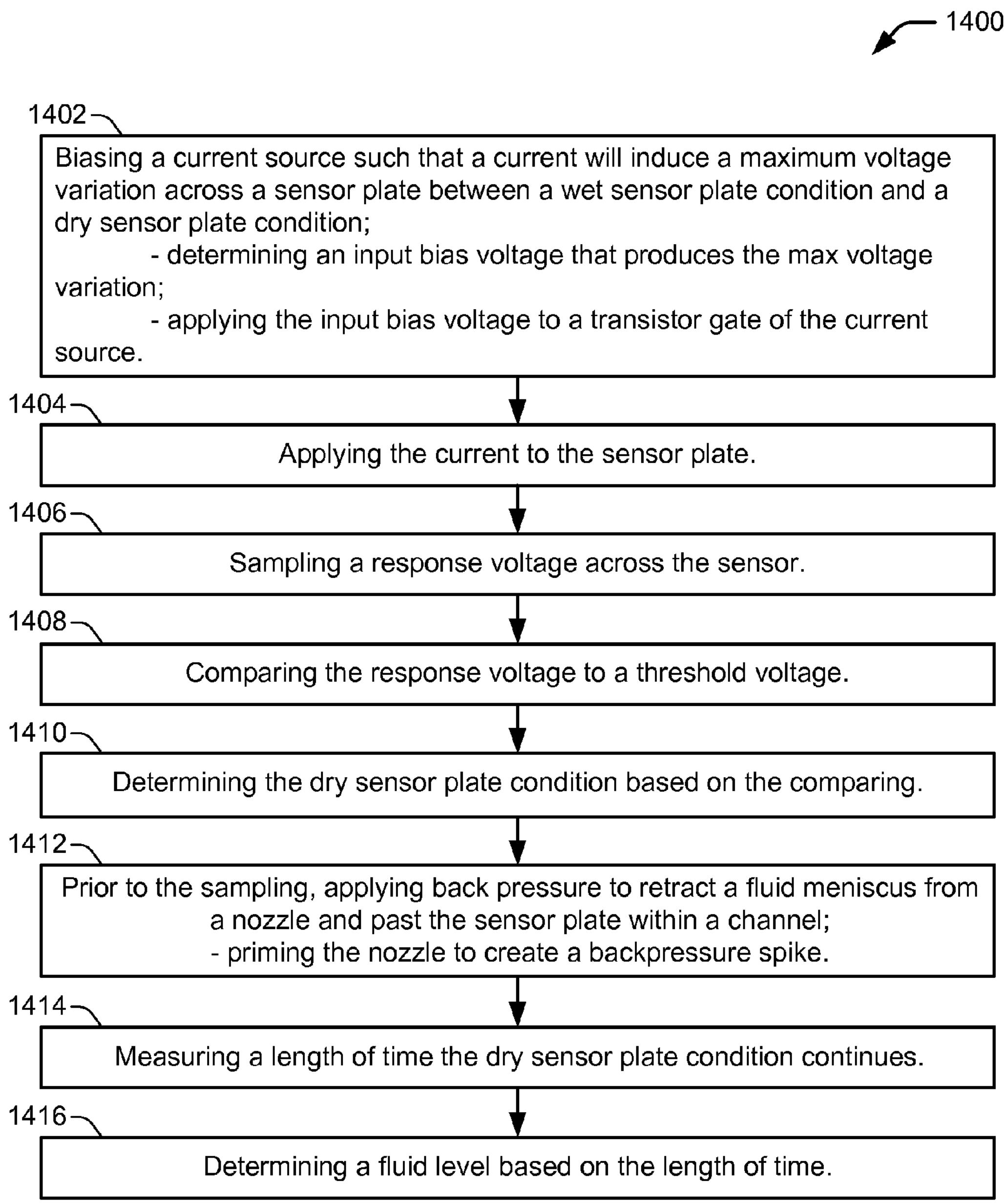

1400
1402
Biasing a current source such that a current will induce a maximum voltage variation across a sensor plate between a wet sensor plate condition and a dry sensor plate condition;
- determining an input bias voltage that produces the max voltage variation;
- applying the input bias voltage to a transistor gate of the current source.
1404
Applying the current to the sensor plate.
1406
Sampling a response voltage across the sensor.
1408
Comparing the response voltage to a threshold voltage.
1410
Determining the dry sensor plate condition based on the comparing.
1412
Prior to the sampling, applying back pressure to retract a fluid meniscus from a nozzle and past the sensor plate within a channel;
- priming the nozzle to create a backpressure spike.
1414
Measuring a length of time the dry sensor plate condition continues.
1416
Determining a fluid level based on the length of time.

FIG. 14

FLUID LEVEL SENSOR AND RELATED METHODS

BACKGROUND

Accurate ink level sensing in ink supply reservoirs for various types of inkjet printers is desirable for a number of reasons. For example, sensing the correct level of ink and providing a corresponding indication of the amount of ink left in A fluid cartridge allows printer users to prepare to replace depleted ink cartridges. Accurate ink level indications also help to avoid wasting ink, since inaccurate ink level indications often result in the premature replacement of ink cartridges that still contain ink. In addition, printing systems can use ink level sensing to trigger certain actions that help prevent low quality prints that might result from inadequate supply levels.

While there are a number of techniques available for determining the level of fluid in a reservoir, or a fluidic chamber, various challenges remain related to their accuracy and cost.

BRIEF DESCRIPTION OF THE DRAWINGS

The present embodiments will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. **1** shows a fluid ejection device embodied as an inkjet printing system suitable for incorporating a fluid level sensor, according to an embodiment;

FIG. **2** shows a bottom view of one end of a TIJ printhead having a single fluid slot formed in a silicon die substrate, according to an embodiment;

FIG. **3** shows a cross-sectional view of an example fluid drop generator, according to an embodiment;

FIG. **4** shows partial top and side views of a MEMS structure in different stages as ink is retracted over the sensor plate during a priming operation, according to an embodiment;

FIG. **5** shows an example of a high level block diagram of an ink level sensor circuit, according to an embodiment;

FIG. **6** shows a range select circuit, according to an embodiment;

FIG. **7** shows an ink level sensor as a black box element, according to an embodiment;

FIG. **8** shows a dry response curve, a wet response curve, and a difference curve over a range of input stimulus, according to an embodiment;

FIG. **9** shows a weak dry response curve, a weak wet response curve, and a weak difference curve, according to an embodiment;

FIG. **10** shows examples of process and environmental variations affecting weak wet and dry response curves, according to an embodiment;

FIG. **11** overlays the wet-dry difference signals from FIG. **10** and shows the difference plotted against the stimulus, illustrating shifts caused by process and environment, according to an embodiment;

FIG. **12** shows difference signal curves based on response instead of on stimulus, according to an embodiment;

FIGS. **13** and **14** show flowcharts of example methods of sensing a fluid level, according to embodiments.

DETAILED DESCRIPTION

Overview of Problem and Solution

As noted above, there are a number of techniques available for determining the level of fluid in a reservoir or fluidic chamber. For example, prisms have been used to reflect or refract light beams in ink cartridges to generate electrical and/or user-viewable ink level indications. Backpressure indicators are another way to determine fluid levels in a reservoir. Some printing systems count the number of drops ejected from inkjet print cartridges as a way of determining ink levels. Still other techniques use the electrical conductivity of the fluid as a level indicator in printing systems. Challenges remain, however, regarding improving the accuracy and cost of fluid level sensing systems and techniques.

Embodiments of the present disclosure provide a fluid level sensor and related methods that improve on prior ink level sensing techniques. The disclosed sensor and methods include a MEMS structure with fluidic elements, a sensor circuit, and a biasing technique to bias the circuit at an optimum operating point. The operating point at which the circuit is biased enables a maximum output difference signal between a dry ink condition (i.e., no ink present) and a wet ink condition (i.e., ink present). The sensor circuit includes a sensor plate in a fluidic channel. Backpressure exerted on the ink in the channel (e.g., while spitting or priming) retracts the ink from a nozzle and pulls it back through the channel over the sensor plate, exposing the plate to air. The circuit includes a current source to supply a current to the sensor plate and induce a voltage response across the plate. The voltage response measured across the plate provides an indication of whether the plate is wet (i.e., indicating ink is present in the fluidic channel) or dry (i.e., indicating air is present in the fluidic channel). The biasing technique employs an algorithm to bias the current source at an optimum point where the amount of current supplied to the sensor plate induces a maximum differential voltage response across the sensor plate between the wet and dry plate conditions in weak signal conditions.

Advantages of the disclosed fluid level sensor and related methods include a high tolerance to contamination from debris left behind in the MEMS structure (e.g., fluidic channels and ink chambers) that enables accurate indications between wet and dry conditions. The sensor cost is controlled because of its use of circuitry and MEMS structures placed onto an existing thermal ink jet print head. The size of the circuitry is such that it can be placed in the space of a few ink-jet nozzles.

In one embodiment, a fluid level sensor includes a sensor circuit having a sensor plate and a current source. The fluid level sensor also includes an algorithm having processor-executable instructions to bias the current source such that current applied to the sensor plate from the current source induces a maximum difference in response voltage between a dry sensor plate condition and a wet sensor plate condition.

In one embodiment, a fluid level sensor includes a current source and a DAC (digital-to-analog convertor) to convert an input code into a bias voltage for the current source. The sensor also includes a sensor plate and a switch to apply current from the current source to the sensor plate. A measurement module determines a wet or dry sensor plate condition by comparing a response voltage on the sensor plate to a threshold.

In another embodiment, a method of sensing a fluid level includes applying stimulus voltage to a sensor circuit in wet and dry conditions. The stimulus voltage has a range from a minimum to a maximum voltage. The method includes measuring a wet response and a dry response over the stimulus range. A difference response between the wet and dry responses is determined, and a peak difference is located in the difference response. The method then determines a peak stimulus voltage that corresponds to the peak difference.

In another embodiment, a method of sensing a fluid level includes biasing a current source such that a current will induce a maximum voltage variation across a sensor plate between a wet sensor plate condition and a dry sensor plate condition. The method also includes applying the current to the sensor plate, sampling a response voltage across the sensor plate, comparing the response voltage to a threshold voltage, and determining the dry sensor plate condition based on the comparing.

Illustrative Embodiments

FIG. **1** illustrates a fluid ejection device embodied as an inkjet printing system **100** suitable for implementing a fluid level sensor and methods as disclosed herein, according to an embodiment of the disclosure. In this embodiment, a fluid ejection assembly is disclosed as a fluid drop jetting printhead **114**. Inkjet printing system **100** includes an inkjet printhead assembly **102**, an ink supply assembly **104**, a mounting assembly **106**, a media transport assembly **108**, an electronic printer controller **110**, and at least one power supply **112** that provides power to the various electrical components of inkjet printing system **100**. Inkjet printhead assembly **102** includes at least one fluid ejection assembly **114** (printhead **114**) that ejects drops of ink through a plurality of orifices or nozzles **116** toward a print medium **118** so as to print onto print media **118**. Print media **118** can be any type of suitable sheet or roll material, such as paper, card stock, transparencies, polyester, plywood, foam board, fabric, canvas, and the like. Nozzles **116** are typically arranged in one or more columns or arrays such that properly sequenced ejection of ink from nozzles **116** causes characters, symbols, and/or other graphics or images to be printed on print media **118** as inkjet printhead assembly **102** and print media **118** are moved relative to each other.

Ink supply assembly **104** supplies fluid ink to printhead assembly **102** and includes a reservoir **120** for storing ink. Ink flows from reservoir **120** to inkjet printhead assembly **102**. Ink supply assembly **104** and inkjet printhead assembly **102** can form either a one-way ink delivery system or a recirculating ink delivery system. In a one-way ink delivery system, substantially all of the ink supplied to inkjet printhead assembly **102** is consumed during printing. In a recirculating ink delivery system, however, only a portion of the ink supplied to printhead assembly **102** is consumed during printing. Ink not consumed during printing is returned to ink supply assembly **104**.

In one embodiment, ink supply assembly **104** supplies ink under positive pressure through an ink conditioning assembly **105** to inkjet printhead assembly **102** via an interface connection, such as a supply tube. Ink supply assembly **104** includes, for example, a reservoir **120**, pumps and pressure regulators (not specifically illustrated). Reservoir **120** may be removed, replaced, and/or refilled. Conditioning in the ink conditioning assembly **105** may include filtering, preheating, pressure surge absorption, and degassing. Ink is drawn under negative pressure from the printhead assembly **102** to the ink supply assembly **104**. The pressure difference between the inlet and outlet to the printhead assembly **102** is selected to achieve the correct backpressure at the nozzles **116**, and is usually a negative pressure between negative 1" and negative 10" of H_2O. However, as the ink supply (e.g., in reservoir **120**) nears its end of life, the backpressure exerted during printing or priming operations increases. The increased backpressure is strong enough to retract the ink meniscus from the nozzle **116** and back through the fluidic channel of the MEMS structure. In one embodiment, printhead **114** includes an ink level sensor **206** (FIG. **2**) that uses the increased backpressure and retracted meniscus to provide an accurate ink level indication toward the end of life of the ink supply.

Mounting assembly **106** positions inkjet printhead assembly **102** relative to media transport assembly **108**, and media transport assembly **108** positions print media **118** relative to inkjet printhead assembly **102**. Thus, a print zone **122** is defined adjacent to nozzles **116** in an area between inkjet printhead assembly **102** and print media **118**. In one embodiment, inkjet printhead assembly **102** is a scanning type printhead assembly. As such, mounting assembly **106** includes a carriage for moving inkjet printhead assembly **102** relative to media transport assembly **108** to scan print media **118**. In another embodiment, inkjet printhead assembly **102** is a non-scanning type printhead assembly. As such, mounting assembly **106** fixes inkjet printhead assembly **102** at a prescribed position relative to media transport assembly **108** while media transport assembly **108** positions print media **118** relative to inkjet printhead assembly **102**.

Electronic printer controller **110** typically includes a processor, firmware, software, one or more memory components including volatile and no-volatile memory components, and other printer electronics for communicating with and controlling inkjet printhead assembly **102**, mounting assembly **106**, and media transport assembly **108**. Electronic controller **110** receives data **124** from a host system, such as a computer, and temporarily stores data **124** in a memory. Typically, data **124** is sent to inkjet printing system **100** along an electronic, infrared, optical, or other information transfer path. Data **124** represents, for example, a document and/or file to be printed. As such, data **124** forms a print job for inkjet printing system **100** and includes one or more print job commands and/or command parameters.

In one embodiment, electronic printer controller **110** controls inkjet printhead assembly **102** for ejection of ink drops from nozzles **116**. Thus, electronic controller **110** defines a pattern of ejected ink drops that form characters, symbols, and/or other graphics or images on print media **118**. The pattern of ejected ink drops is determined by the print job commands and/or command parameters from data **124**. In one embodiment, electronic controller **110** includes a biasing algorithm **126** having executable instructions to execute on controller **110**. The biasing algorithm **126** executes to control the ink level sensor **206** (FIG. **2**) and to determine an optimum operating/bias point that produces a maximum voltage response difference from the sensor **206** between a wet condition (i.e., when ink is present) and a dry condition (when air is present). Electronic controller **110** additionally includes a measurement module **128** having executable instructions to execute on controller **110**. After an optimum bias point is determined, measurement module **128** executes to initiate a measurement cycle that controls the ink level sensor **206** and determines an ink level based on a measured time period during which a dry condition persists in a fluidic channel of the MEMS structure.

In the described embodiments, inkjet printing system **100** is a drop-on-demand thermal inkjet printing system with a thermal inkjet (TIJ) printhead **114** suitable for implementing an ink level sensor as disclosed herein. In one implementation, inkjet printhead assembly **102** includes a single TIJ printhead **114**. In another implementation, inkjet printhead assembly **102** includes a wide array of TIJ printheads **114**.

While the fabrication processes associated with TIJ printheads are well suited to the integration of the disclosed ink level sensor, other printhead types such as a piezoelectric printhead can also implement such an ink level sensor. Thus, the disclosed ink level sensor is not limited to implementation in a TIJ printhead **114**.

FIG. **2** shows a bottom view of one end of a TIJ printhead **114** having a single fluid slot **200** formed in a silicon die substrate **202**, according to an embodiment of the disclosure. Although printhead **114** is shown with a single fluid slot **200**, the principles discussed herein are not limited in their application to a printhead with just one slot **200**. Rather, other printhead configurations are also possible, such as printheads with two or more fluid slots, or printheads that use various sized holes to bring ink to fluidic channels and chambers. The fluid slot **200** is an elongated slot formed in the substrate **202** that is in fluid communication with a fluid supply, such as a fluid reservoir **120**. Fluid slot **200** has fluid drop generators **300** arranged along both sides of the slot that include fluid chambers **204** and nozzles **116**. Substrate **202** underlies a chamber layer having fluid chambers **204** and a nozzle layer having nozzles **116** formed therein, as discussed below with respect to FIG. **3**. However, for the purpose of illustration, the chamber layer and nozzle layer in FIG. **2** are assumed to be transparent in order to show the underlying substrate **202**. Therefore, chambers **204** and nozzles **116** in FIG. **2** are illustrated using dashed lines.

In addition to drop generators **300** arranged along the sides of the slot **200**, the TIJ printhead **114** includes one or more fluid (ink) level sensors **206**. A fluid level sensor **206** generally includes a MEMS structure and an integrated sensor circuit **208**. A MEMS structure includes, for example, fluid slot **200**, fluidic channels **210**, fluid chambers **204** and nozzles **116**. A sensor circuit **208** includes a sensor plate **212** located on the floor of a fluidic channel **210**, and other circuitry **214**. The other circuitry **214** includes, for example, a current source, a buffer amplifier, a DAC (digital-to-analog convertor), an ADC (analog-to-digital convertor), and measurement circuitry. The sensor plate **212** is a metal plate formed, for example, of tantalum. Portions of the other circuitry **214**, such as the ADC and measurement circuitry, may not all be in one location on substrate **202**, but instead may be distributed on substrate **202** in different locations. The fluid sensor **206** and sensor circuit **208** are discussed in greater detail below with respect to FIGS. **4** and **5**.

FIG. **3** shows a cross-sectional view of an example fluid drop generator **300**, according to an embodiment of the disclosure. Each drop generator **300** includes a nozzle **116**, a fluid chamber **204**, and a firing element **302** disposed in the fluid chamber **204**. Nozzles **116** are formed in nozzle layer **310** and are generally arranged to form nozzle columns along the sides of the fluid slot **200**. Firing element **302** is a thermal resistor formed of a metal plate (e.g., tantalum-aluminum, TaAl) on an insulating layer **304** (e.g., polysilicon glass, PSG) on a top surface of the silicon substrate **202**. A passivation layer **306** over the firing element **302** protects the firing element from ink in chamber **204** and acts as a mechanical passivation or protective cavitation barrier structure to absorb the shock of collapsing vapor bubbles. A chamber layer **308** has walls and chambers **204** that separate the substrate **202** from the nozzle layer **310**.

During printing, a fluid drop is ejected from a chamber **204** through a corresponding nozzle **116**, and the chamber **204** is then refilled with fluid circulating from fluid slot **200**. More specifically, an electric current is passed through a resistor firing element **302** resulting in rapid heating of the element. A thin layer of fluid adjacent to the passivation layer **306** that covers firing element **302** is superheated and vaporizes, creating a vapor bubble in the corresponding firing chamber **204**. The rapidly expanding vapor bubble forces a fluid drop out of the corresponding nozzle **116**. When the heating element cools, the vapor bubble quickly collapses, drawing more fluid from fluid slot **200** into the firing chamber **204** in preparation for ejecting another drop from the nozzle **116**.

FIG. **4** shows partial top and side views of a MEMS structure in different stages as ink is retracted over the sensor plate during a priming operation, according to an embodiment of the disclosure. As noted above, a fluid level sensor **206** generally includes a MEMS structure having a fluidic channel **210**, a fluid chamber **204** and a dedicated sensor nozzle **116**. A fluid level sensor **206** also includes a sensor circuit **208** with a sensor plate **212** located on the floor of a fluidic channel **210**. The sensor circuit **208** operates to detect the presence or absence of fluid (ink) in the fluidic channel during a priming operation. As the ink supply in reservoir **120** nears its end of life, the backpressure exerted during printing or priming operations becomes strong enough to retract the ink meniscus from the nozzle **116** and back through the fluidic channel **210**, exposing the sensor plate **212** to air. FIG. **4**(*a*) shows a normal state where ink **400** fills the chamber **204** and forms an ink meniscus **402** within the nozzle **116**. In this state, the sensor plate **212** is in a wet condition as it is covered with the ink that fills the fluidic channel **210**. During a priming operation, or a normal ink drop ejection printing operation, a backpressure is exerted on the ink in the fluidic channel **210** which retracts the ink meniscus **402** from the nozzle and pulls it back within the channel as shown in FIG. **4**(*b*). As the ink supply in reservoir **120** nears its end of life, this backpressure increases, as does the time it takes for the ink to flow back into the channel **210** and nozzle **116**. As shown in FIG. **4**(*c*), the increased backpressure pulls the ink meniscus far enough back into the channel **210** that the sensor plate **212** is exposed to air drawn in through nozzle **116**. As discussed below, the sensor circuit **208** uses the exposed sensor plate **212** to determine an accurate ink level near the end of life of the ink supply.

FIG. **5** shows an example of a high level block diagram of a fluid level sensor circuit **208**, according to an embodiment of the disclosure. The sensor circuit **208** includes a DAC (digital-to-analog convertor) **500**, an input S&H (sample and hold element) **502**, a current source **504**, a sensor plate **212**, a switch **506**, an output S&H **508**, an ADC (analog-to-digital convertor) **510**, a state machine **512**, a clock **514**, and a number of registers such as registers 0xD0-0xD6, **516**. Operation of the sensor circuit **208** begins with configuring (i.e., biasing) the current source **504** with the DAC **500** and input S&H **502** while switch **506** is closed to short out the sensor plate **212**. The biasing algorithm **126**, discussed in greater detail below, executes on controller **110** to determine a stimulus (input code) to apply to register 0xD2 that yields an optimum bias voltage from the DAC **500** with which to bias the current source **504**.

After the current source **504** is biased, the measurement module **128** executes on controller **110** and initiates a fluid level measurement cycle during which it controls the sensor circuit **208** through state machine **512**. When it is time to measure, the state machine **512** coordinates the measurement by stepping the circuit **208** through several stages that prepare the circuit, take the measurements, and return the circuit to idle. In a first step, the state machine **512** initiates a priming event. The priming event spits or ejects ink from the nozzle **116** to clear the nozzle and chamber **204** of ink, and creates a backpressure spike in the fluidic channel **210**.

The state machine **512** then provides a delay period. The delay period is variable, but typically lasts on the order of between 2 and 32 microseconds. After the delay, a first circuit preparation step opens switch **506**, applying current from the current source **504** to the sensor plate **212**. The applied current charges the plate capacitance and induces a voltage response across the plate.

Note that the current supplied from the current source **504** is based on the following relationship:

$$I\alpha(V_{gs}-V_t)^2$$

where Vgs is the bias voltage from the DAC **500**. Vgs is the gate-to-source voltage and Vt is the gate threshold voltage of a current-producing transistor of the current source **504**. Current source **504** includes a range select circuit, shown generally in FIG. **6**, that enables the voltage from the DAC **500** to be applied to one of three current-producing transistors **600**, **602**, **604**, that produce current for the ranges 1×, 10× and 100×. Once a transistor is selected to produce current, the voltage from the DAC **500** is applied at the gate of the selected transistor which determines the amount of current supplied by current source **504**.

In a second circuit preparation step, the state machine **512** opens the switch **506** and provides a second delay period, which again lasts on the order of between 2 and 32 microseconds. After the second delay, the state machine **512** causes the output S&H element **508** to sample (i.e., measure) the analog response voltage at the sensor plate **212** and to hold it. The state machine **512** then initiates a conversion through ADC **510** that converts the sampled analog response voltage to a digital value that is stored in a register, 0xD6. The register holds the digital response voltage until the measurement module **128** reads the register. The circuit **208** is then put in an idle mode until another measurement cycle is initiated.

The measurement module **128** compares the digitized response voltage to an R_{detect} threshold to determine if the sensor plate is in a dry condition. If the measured response exceeds R_{detect} then the dry condition is present. Otherwise the wet condition is present. (Calculation of the R_{detect} threshold is discussed below). Detecting a dry condition indicates that the backpressure has pulled the ink in the fluidic channel **210** back far enough to expose the sensor plate **212** to air. Through additional measurement cycles, the length of time that the dry condition persists (i.e., while the sensor plate is exposed to air) is measured and used to interpolate the magnitude of backpressure creating the dry condition. Since the backpressure increases predictably toward the end of the life of the ink supply, an accurate determination of the ink level can then be made.

As noted above, the biasing algorithm **126** executes on controller **110** to determine an optimum bias voltage from the DAC **500** with which to bias the current source **504**. The biasing algorithm **126** controls the fluid level sensor **206** (i.e., the sensor circuit **208** and MEMS structure) while determining the bias voltage. From the perspective of the biasing algorithm **126**, as shown in FIG. **7**, the fluid level sensor **206** is a black box element that receives an input or stimulus and provides an output or response. An input voltage is set using a 0-255 (8-bit) number (input code) applied to register 0xD2 of sensor circuit **208**. The input number or code in register 0xD2 is a stimulus that is applied to the DAC **500**, and the analog voltage output from the DAC is the stimulus multiplied by 10 mV. Therefore, the range of analog bias voltage from the DAC **500** that is available for biasing the current source **504** is 0-2.55V. The output or response from the sensor circuit **208** is a digital code stored in an 8-bit register 0xD6.

The biasing algorithm uses the stimulus-response relationship of the sensor circuit **208** between input codes and output codes to provide an optimum output delta signal (i.e., a maximum response voltage) between when the sensor plate **212** is wet (i.e., when ink is present in MEMS fluidic channel **210** and covers the plate) and when the sensor plate **212** is dry (i.e., when ink has been pulled out of the MEMS fluidic channel **210** and air surrounds the plate). As shown in FIG. **8**, when the stimulus (input codes) is swept from its minimum to its maximum pre-charge voltage count (i.e., 0-255; S_{min} to S_{max}), the response (output codes) generate response waveforms that progress through three distinct regions: Off, Active and Saturated. Together, the three regions form the shape of a lazy "S". FIG. **8** shows a dry response curve **800**, a wet response curve **802**, and a difference curve **804** that indicates the difference between the wet and dry response curves over the range of input stimulus. The FIG. **8** response curves depict favorable conditions where the responses are strong. In general, the largest signal delta (i.e., largest difference response curve) occurs between the case where the sensor plate **212** is fully wet with a full channel of ink, and the case where the sensor plate **212** is fully dry with full contact with air in the channel.

Although the response curves vary between the presence and absence of fluid/ink (i.e., between wet and dry conditions), the amount of variance is stronger when there is little or no contamination present in the MEMS structure, such as conductive debris and ink residue. Therefore, the response is initially strong as shown by the strong response curves in FIG. **8**. However, over time the MEMS structure may become contaminated with ink residue in the fluidic channels and chambers, and the dry response in particular will degrade and become closer to the wet response. Contamination causes conduction in the dry case that makes the dry response weak, which results in a weak difference between the dry and wet response. FIG. **9** shows weak dry **900**, wet **902**, and difference **904** response curves where unfavorable conditions such as contamination in the MEMS structure have degraded the responses. As can be seen in FIG. **9**, the difference between the weak wet and weak dry response curves is much less than the difference shown in the strong response curves of FIG. **8**. The strong difference curve **804** shown in FIG. **8** provides a strong distinction between a wet and dry condition that can be readily evaluated. However, under weak response conditions, finding a distinction between wet and dry conditions is more challenging because of the weak difference. The biasing algorithm **126** finds the optimum point of difference in the weak response difference curve **904** (i.e., shown in FIG. **9**) where fluid/ink level measurements will provide the maximum response between wet and dry conditions.

FIGS. **10** (*a*.**1**, *a*.**2**, *a*.**3**, *b*.**1**, *b*.**2**, *b*.**3**, *c*.**1**, *c*.**2**, *c*.**3**) show examples of weak dry response curves **1000** and weak wet response curves **1002** and their variations in response to differences in process and environmental conditions, such as manufacturing process, supply voltage and temperature (PV&T), according to an embodiment of the disclosure. FIGS. **10**(*a*.**1**), (*a*.**2**) and (*a*.**3**) show example curves over input stimulus ranges 1×, 10× and 100×, respectively, with worst (W) case processing conditions, a 5.5 volt supply, and 15 degrees centigrade temperature (referenced in FIGs. as "W;5.5V;15C"). FIGS. **10**(*b*.**1**), (*b*.**2**) and (*b*.**3**) show example curves over input stimulus ranges 1×, 10× and 100×, respectively, with best case (B) processing conditions, a 4.5 volt supply, and 110 degrees centigrade temperature (referenced in FIGs. as "B;4.5V;110C"). FIGS. **10**(*c*.**1**), (*c*.**2**) and (*c*.**3**) show example curves over input stimulus ranges 1×, 10× and 100×, respectively, with typical (T) processing conditions, a 5.0 volt supply, and 60 degrees centigrade temperature (referenced in FIGs. as "T;5.0V;60C"). In some cases, the active regions of the response curves change in slope due to variations in PV&T. In other cases, the active regions of the response curves shift their placement, starting earlier or later in the off region. The dry and wet response curves in FIGS. **10** (*a*), (*b*) and (*c*), show such variations in slopes and starting points that can result from varying PV&T conditions. The difference curves **1004** in FIGS. **10** (*a*), (*b*) and (*c*), show the difference between the wet and dry response curves over the range of input stimulus and over variations in PV&T conditions.

FIG. **11** shows the difference between the dry response and wet response plotted against the stimulus, according to an embodiment of the disclosure. The difference curves **1004** shown in FIG. **10** are overlayed to form FIG. **11**. The intention is to illustrate that the height of the peak of the difference curves, the slope of the approach and decay of the curves, and the placement of the center of the stimulus axis along the curves, all vary across PV&T.

FIG. **12** shows an example of composite difference curves **1200** plotted against the wet response, according to an embodiment of the disclosure. By shifting the basis of the difference curves to response, instead of stimulus, a measure of isolation from PV&T differences is achieved. The biasing algorithm **126** finds a solution where the optimum difference point is located in the weak difference case that provides a maximum ink level measurement response between wet and dry conditions. Therefore, the solution should be tolerant to such variations in PV&T, as well as provide as large a margin as possible. Accordingly, as shown in FIG. **12**, a large amount of the PV&T variance can be removed by viewing the difference curve **1004** as a function of the wet response curve **1002**, instead of as a function of the input stimulus. This is because there is a large variation in output value for a given stimulus over process, voltage and temperature (PV&T). However, the difference between the dry condition (no ink) and the wet condition (ink present) does not vary as much over PV&T, so using this difference subtracts off much of the PV&T-induced variation. The composite of the difference curves encompasses the area formed by overlaying many difference curves determined across all process and environmental (PV&T) conditions. Thus, the region above the composite difference represents viable signal response area that is independent of PV&T conditions. The center of the composite difference represents the location where ink level measurements should be made in order to achieve a peak response (R_{peak}) that maximizes the voltage response between a dry condition and a wet condition. The location of the R_{peak} response is expressed as a percentage of the span between the minimum and maximum wet response, R_{min} and R_{max}. Thus, the location of R_{peak} on the composite difference curve **1200** is called $R_{pd\ \%}$. In addition, during a measurement cycle, the height of the peak of the composite difference curve **1200** at location $R_{pd\ \%}$ represents the minimum difference expected (as a percentage of the span between R_{min} and R_{max}) when the dry condition is present, and can be called $D_{min\ \%}$.

The biasing algorithm **126** determines an input stimulus value S_{peak}, that produces the peak response R_{peak} located on the composite difference curve **1200** at Rpd %. The algorithm inputs a minimum stimulus (S_{min}) at register 0xD2 and samples the response in register 0xD6. The algorithm also inputs a maximum stimulus (S_{max}) at register 0xD2 and samples the response in register 0xD6. These two values in register 0xD6 are the extremes of response, R_{min} and R_{max} respectively. The peak response value R_{peak} can then be calculated as follows:

$$R_{peak}=R_{min}+(R_{pd\ \%}*(R_{max}-R_{min}))$$

The corresponding stimulus value, S_{peak}, can then be found by a variety of approaches. The stimulus can, for example, be swept from S_{min} to S_{max}, stopping when the response reaches R_{peak}. Another approach is to use a binary search. The stimulus value S_{peak} that produces the peak response R_{peak} is the input code applied to register 0xD2 to optimally bias the current source **504** in sensor circuit **208** such that a maximum response can be measured across the sensor plate **212** between a dry plate condition and a wet plate condition.

As noted above, in a measurement cycle the measurement module **128** determines if the sensor plate **212** is in a dry condition by comparing the response voltage measured across the plate to an R_{detect} threshold. If the measured response exceeds R_{detect} then the dry condition is present. Otherwise the wet condition is present. The R_{detect} threshold is calculated by the following equation:

$$R_{detect}=R_{peak}+((R_{max}-R_{min})*(D_{min\ \%}/2))$$

The minimum difference $D_{min\ \%}$ expected in the response voltage is split (i.e., divided by 2) to share the noise margin between the dry condition case and the wet condition case.

FIG. **13** shows a flowchart of an example method **1300** of sensing a fluid level, according to an embodiment of the disclosure. Method **1300** is associated with the embodiments discussed above with respect to FIGS. **1**-**12**. Method **1300** begins at block **1302**, with applying stimulus voltage to a sensor circuit in wet and dry conditions. The applied stimulus voltage has a range from a minimum to a maximum voltage. At block **1304**, a wet response and a dry response are measured over the stimulus range. The measuring includes sampling voltage across a sensor plate in a fluid channel that contains fluid, and sampling voltage across a sensor plate in a fluid channel from which the fluid has been withdrawn by an applied backpressure. The method **1300** continues at block **1306** with finding a difference response between the wet and dry responses, and at block **1308** a peak difference in the difference response is located. At block **1310**, a peak stimulus that corresponds to the peak difference is determined. This step includes determining a wet response value that corresponds to the peak difference, and correlating the wet response value to the peak stimulus voltage. At block **1312** of method **1300**, a current source of the sensor circuit is biased using the peak stimulus, and at block **1314**, current from the current source is applied to the sensor plate. At block **1316**, a voltage response across the sensor plate is sampled. The sensor plate voltage is compared with a threshold voltage at block **1318** to determine a dry plate condition, and the time period over which the dry plate condition persists is measured at block **1320**. At block **1322** of method **1300**, a fluid level is determined based on the time period.

FIG. **14** shows a flowchart of another example method **1400** of sensing a fluid level, according to an embodiment of the disclosure. Method **1400** is associated with the embodiments discussed above with respect to FIGS. **1**-**12**. Method **1400** begins at block **1402**, with biasing a current source such that current from the current source will induce a maximum voltage variation across a sensor plate between a wet sensor plate condition and a dry sensor plate condition. Biasing the current source includes determining an input bias voltage that produces the maximum voltage variation and applying the input bias voltage to a transistor gate of the current source. Finding the input bias voltage includes applying a range of stimulus to the current source from a minimum stimulus voltage to a maximum stimulus voltage for both the wet sensor plate condition and the dry sensor plate condition. Applying the stimulus includes applying an 8-bit number ranging from zero to 255 to a DAC, and providing the output from the DAC as the 8-bit number multiplied by an analog voltage (e.g., 1 mV, 10 mV, 100 mV). Finding the input bias voltage also includes determining a wet condition voltage response and a dry condition voltage response across the sensor plate over the range of stimulus, determining a difference response between the wet condition voltage response and the dry condition voltage response, determining a peak difference response from the difference response, and locating a peak stimulus voltage that produces the peak difference response.

At block **1404** of method **1400**, the current produced from the biased current source is applied to the sensor plate, and at block **1406** a response voltage across the sensor is sampled. The response voltage is compared with a threshold voltage at block **1408** to determine a dry plate condition as shown at block **1410**. At block **1412**, prior to the sampling, back pressure is applied to retract the meniscus from the nozzle and past the sensor plate within a fluidic channel. The back pressure is applied through priming the nozzle which creates a backpressure spike. At block **1414**, the length of time that the dry sensor plate condition continues is measured, and at block **1416** a fluid level in the reservoir is determined based on the length of time.

What is claimed is:

1. A fluid level sensor comprising:

a nozzle;

a fluid channel;

a sensor plate on a floor of the channel;

a current source coupled to the sensor plate to induce a voltage across the sensor plate; and

a sensor circuit to determine a voltage response of the sensor plate to the current source, the voltage response indicating whether fluid is present on the sensor plate.

2. A sensor as in claim **1**, the sensor circuit further comprising a state machine to initiate a nozzle priming event, wherein the sensor circuit determines the voltage response during the nozzle priming event.

3. A fluid level sensor as in claim **1**, wherein the sensor circuit determines an ink level based on a measured time period during which the voltage response of the sensor plate indicates a dry condition in the fluid channel.

4. A fluid level sensor as in claim **1**, the sensor circuit comprising an electronic controller programmed to determine a bias for the current source such that the induced voltage across the sensor plate has a maximum differential voltage response between wet and dry sensor plate conditions.

5. A fluid level sensor as in claim **2**, the sensor circuit further comprising: an input register; and a digital to analog converter (DAC) to receive an input code from the input register and provide a bias voltage to bias the current source.

6. A sensor as in claim **5**, the sensor circuit further comprising an input sample and hold to sample the bias voltage from the DAC and apply the bias voltage to the current source.

7. A sensor as in claim **6**, the sensor circuit further comprising a switch to short out the sensor plate in a closed position during biasing of the current source, and to apply current from the current source to the sensor plate in an open position.

8. A sensor as in claim **5**, wherein the current source comprises three current producing transistors to produce current in three different current ranges.

9. A sensor as in claim **8**, wherein the current source further comprises a range select circuit to apply voltage from the DAC to one of the three current producing transistors.

10. A sensor as in claim **1**, the sensor circuit further comprising an output sample and hold to sample an analog response voltage at the sensor plate.

11. A sensor as in claim **10**, the sensor circuit further comprising an analog to digital converter (ADC) to convert the analog voltage response to a digital value.

12. A sensor as in claim **11**, the sensor circuit further comprising: an output register to store the digital value.

13. An inkjet printhead comprising the fluid level sensor of claim **1**, the printhead further comprising:

a fluid slot, and

the fluid channel disposed to fluidically couple the nozzle to the fluid slot.

14. An inkjet printhead as in claim **13**, further comprising: a DAC to convert an input code into a bias voltage to bias the current source; and an input sample and hold element to sample the bias voltage from the DAC and apply it to the current source.

15. An inkjet printhead as in claim **14**, further comprising an ADC to convert the voltage response to a digital value.

16. An inkjet printhead as in claim **15**, further comprising: an input register to provide the input code to the DAC; and an output register to store the digital value.

17. An inkjet printhead as in claim **15**, further comprising a switch to short out the sensor plate in a closed position during biasing of the current source, and to apply current from the current source to the sensor plate in an open position.

18. An inkjet printhead as in claim **17**, further comprising a state machine to control the switch, the sample and hold elements, the DAC, and the ADC.

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